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Operation

HARDTACK

April - October 1958

Project 8.1

EFFECTS on MATERIALS of THERMAL RADIATION from NUCLEAR DETONATIONS (U)

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Report on
OPERATION HARDTACK—PROJECT 8.1

(6) (21)

EFFECTS on MATERIALS of THERMAL RADIATION from NUCLEAR DETONATIONS (U)

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FOREWORD

This report presents the final results of one of the projects participating in the military-effect programs of Operation Hardtack. Overall information about this and the other military-effect projects can be obtained from ITR–1660, the "Summary Report of the Commander, Task Unit 3." This technical summary includes: (1) tables listing each detonation with its yield, type, environment, meteorological conditions, etc.; (2) maps showing shot locations; (3) discussions of results by programs; (4) summaries of objectives, procedures, results, etc., for all projects; and (5) a listing of project reports for the military-effect programs.

ABSTRACT

of this report
The primary objective was to determine the adequacy of laboratory methods for investigating the protection afforded by clothing against the thermal radiation from nuclear weapons. The skin simulant that has been used extensively in the laboratory was used as the receiving instrument. The other objective was to make basic thermal-radiation measurements on the earth's surface near ground zero and at great distances during very-high-altitude detonations (Shots Teak and Orange).

To be investigated in the skin-simulant study was the adequacy of laboratory thermal-radiation sources as to time variation of irradiance, area of irradiation, and source spectrum. To determine the adequacy of laboratory methods in these respects, the skin simulants were exposed in three spectrally different absorbing situations and behind apertures of four different diameters. Exposures were made during Shots Yellowwood and Walnut. The resulting skin-simulant temperatures, which are related to burn level, were compared with each other and with those predicted from laboratory results.

The average differences between the laboratory and field in maximum temperature rise in the spectrally neutral specimens were 15 percent, the laboratory values being lower. This difference includes an estimated 10-percent experimental uncertainty; the remaining discrepancy is attributed to differences in the time variation of irradiance.

In both detonations the temperature rises of the simulants covered by the infrared-reflecting, hot-wet (poplin) uniform yielded lower temperature rises than those obtained with the equivalent pulse delivered by the laboratory source. These lower temperatures are rational and result from the lower radiating temperatures of the surface detonations.

The dependence of maximum temperature rise on the diameter of the irradiated area, for the uncovered simulants and simulants with cloth in contact, was as predicted by the laboratory measurements.

The measured irradiance histories of both Shots Yellowwood and Walnut were in good agreement with the generalized field pulse from zero time to approximately eight times the time to the second irradiance maximum at which point obscuration set in, greatly attenuating the remainder or "tail" of each pulse. Although the attenuation of the tail did not affect the maximum temperature rise generated in the simulant assemblies, it makes the total pulse integral an unreliable index of the total flux in the corresponding generalized pulse.

The radiant exposures and irradiance histories were measured during Shots Teak and Orange at four surface stations and one airborne station. Data obtained at these stations was employed to document the thermal radiation for the retinal-burn studies of Project 4.1. Skin simulants were exposed at the nearest station for each shot to obtain data for skin-burn studies.

The average radiant exposures during Shot Teak were 1.3, 0.28, 0.075, 0.0007, and 0.019 cal/cm^2 for slant ranges of 41.4, 85, 164, 299, and 299 nautical miles, the last station being airborne.

The irradiance histories were obtained with a receiver system that had a limited time response and a sensitivity in only the visible and near-infrared regions.

The irradiance history was not resolved for the first 10 msec; thereafter the irradiance decayed in a regular manner until 200 msec, when the trace deflections were too small for definition. The irradiance histories, when normalized at 100 msec, were the same within 5 percent at each of the stations.

The average radiant exposures measured for Shot Orange were 1.08, 0.08, 0.09, 0.012, and

0.012 cal/cm^2 at slant ranges of 20.6, 75.2, 88.4, 142.8, and 225 nautical miles, the last station being airborne.

The irradiance history for Shot Orange was fairly constant from 40 to 170 msec and then decayed to a small value in another 70 msec.

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Part I
EVALUATION of LABORATORY METHODS for INVESTIGATING the PROTECTION AFFORDED by UNIFORMS

OBJECTIVE

The objective of the skin-simulant study was to determine the adequacy of the laboratory methods in studying the effects of intense thermal radiation on biological systems. More specifically, the purpose of this investigation was to determine the adequacy of the irradiation area, time variation of irradiance, and spectrum of the laboratory sources employed in evaluating the protection afforded to personnel by military clothing.

BACKGROUND AND THEORY

Thermal-radiation damage to materials and to personnel has been studied extensively at the Naval Material Laboratory (NML), including both the critical radiant exposures required to cause typical damage to representative materials and the protection afforded to skin by various clothing assemblies. The purpose of Project 8.1, Operation Hardtack, was to validate the methods employed in these laboratory studies, the results of which are important to military and civil-defense groups in evaluating operational and tactical situations.

A skin simulant utilizing a temperature criterion for burn levels has been developed by NML for use as a substitute for animal and human skin in studies of subfabric radiant-energy burns (References 1, 2, and 3).

In a full-scale experiment during Operation Upshot-Knothole (Reference 4), a polyethylene skin simulant was employed to evaluate the protection provided by uniform systems. Since that time, changes have been made in both the skin simulant and the evaluation techniques.

The improved skin simulant has the thermal properties of human skin and closely resembles it in optical characteristics (Reference 3). This skin simulant includes a fine-wire thermocouple embedded at a depth of 0.05 cm, permitting the use of a maximum-temperature burn criterion with minor qualifications.

To determine the adequacy of laboratory methods, NML employed the simulant in the testing of the smaller nuclear devices during Operation Plumbbob (Reference 5). A similar investigation was made during Operation Hardtack. Laboratory results predicted to within 20 percent the temperature rises in the field, for the skin simulants in contact with the clothing, and for the unclothed simulants. For the arrangements in which a space existed between the simulant and the clothing, the temperatures in the field were often much lower than those predicted in the laboratory. This difference was attributed to the action of the blast in the field. The irradiance variation and the spectrum of the laboratory source were found to be adequate for studies of the protective qualities of uniforms. The results for exposures employing irradiation areas as small as 9 mm in diameter do not agree with, but can be correlated with, those involving larger areas.

Reference 6 contains a review of the development of a plastic, physical skin simulant for evaluating subfabric flash burns.

OPERATIONS

The original plan was to participate in Shots Elder, Yellowwood, and Poplar. For technical reasons outside project control, Shots Yellowwood and Walnut were the only shots available. For these, a station was instrumented on Site Olive at a distance of 25,500 feet from ground zero.

The temperature histories of the simulant were recorded on oscillographic equipment. The equipment was installed in a shelter below ground, to minimize the effects of blast and prompt- and residual-gamma radiation. Protective covers were removed from the exposure assemblies

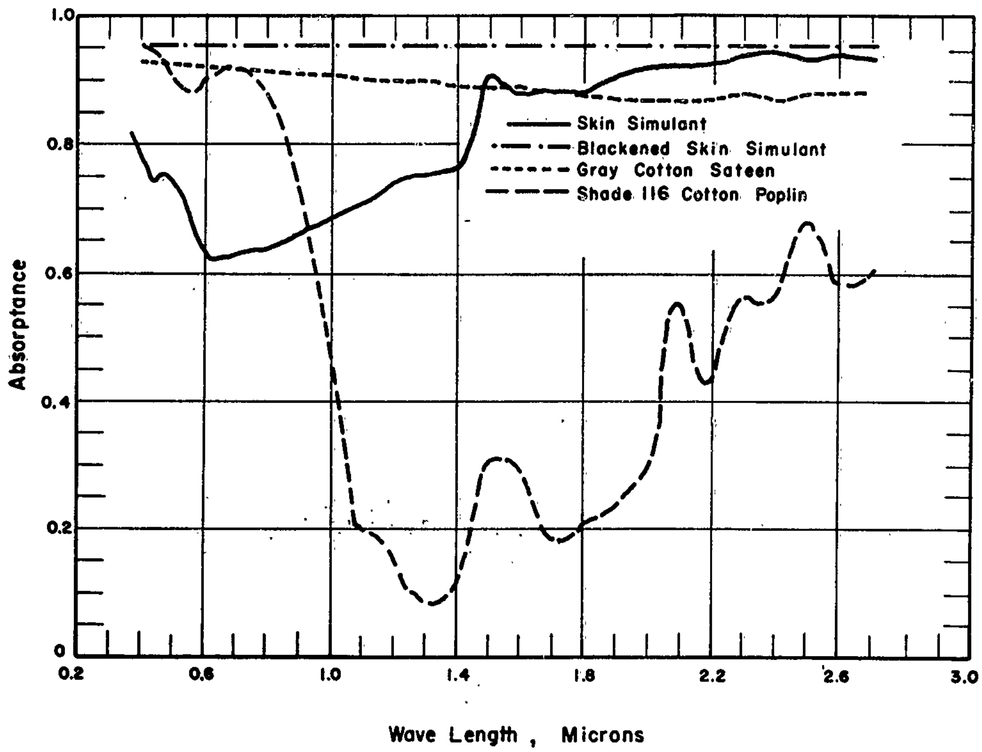

Figure 1.1 Spectral absorptances of NML skin simulant and standard fabrics.

prior to the detonation. The various assemblies and recording equipment were recovered as soon after the detonation as practicable.

INSTRUMENTATION

For each shot, the station was instrumented with 29 simulant units. The thermocouples embedded in the simulants were connected to Heiland oscillographs, which recorded the change in thermal emf. To minimize any possible obscuration of thermal radiation, the assemblies were mounted 10 feet above the ground on panels secured to station structures.

Six basically different uniform-simulant configurations were employed: (1) the NML skin simulant, uncovered; (2) the NML skin simulant, blackened; (3) the Army hot-wet uniform assembly (5-oz/yd^2 cotton poplin, Shade 116, over 4-oz/yd^2 white cotton sheeting) in firm contact with the simulant; (4) the hot-wet uniform spaced 5 mm from the simulant; (5) a dark-gray, 9-oz/yd^2 cotton sateen over the 4-oz/yd^2 white cotton sheeting in firm contact with the simulant; and (6) the dark-gray sateen assembly spaced 5 mm from the simulant.

The spectral absorptances of the simulant and the two outer fabrics were measured and are shown in Figure 1.1. The radiant absorptances, as computed for the carbon-arc spectrum and a 3,000 K black-body radiator, are given in Table 1.1. Figure 1.1 shows that the spectral selec-

tivity of the skin simulant is opposite in trend to that of the poplin. That is, the simulant has a generally higher absorptance in the infrared than it has in the visible, while the poplin has a markedly higher absorptance in the visible than the infrared. Therefore, significant differences in the spectra of the laboratory source and the field thermal pulse should result in differences in the temperature rises of the backing. If the carbon-arc laboratory source is deficient in vis-

TABLE 1.1 RADIANT ABSORPTANCES OF SKIN SIMULANT AND STANDARD FABRICS

Specimen	Radiant Absorptance	
	Carbon Arc	3,000 K Black Body
Skin simulant, uncovered	0.72	0.76
Skin simulant, blackened	0.95	0.95
Poplin, Shade 116, 5 oz/yd^2	0.63	0.31
Sateen, gray, 9 oz/yd^2	0.91	0.91

ible radiation, the temperatures obtained in the laboratory under the poplin would be lower than those from the nuclear device, and those for the uncovered simulant would be higher in the laboratory than in the field. Deficiencies in the infrared regions would cause inverse effects. The blackened simulant and the gray sateen are essentially neutral; consequently, differences in the spectra of the two sources should not affect the temperature rise of the uncovered blackened

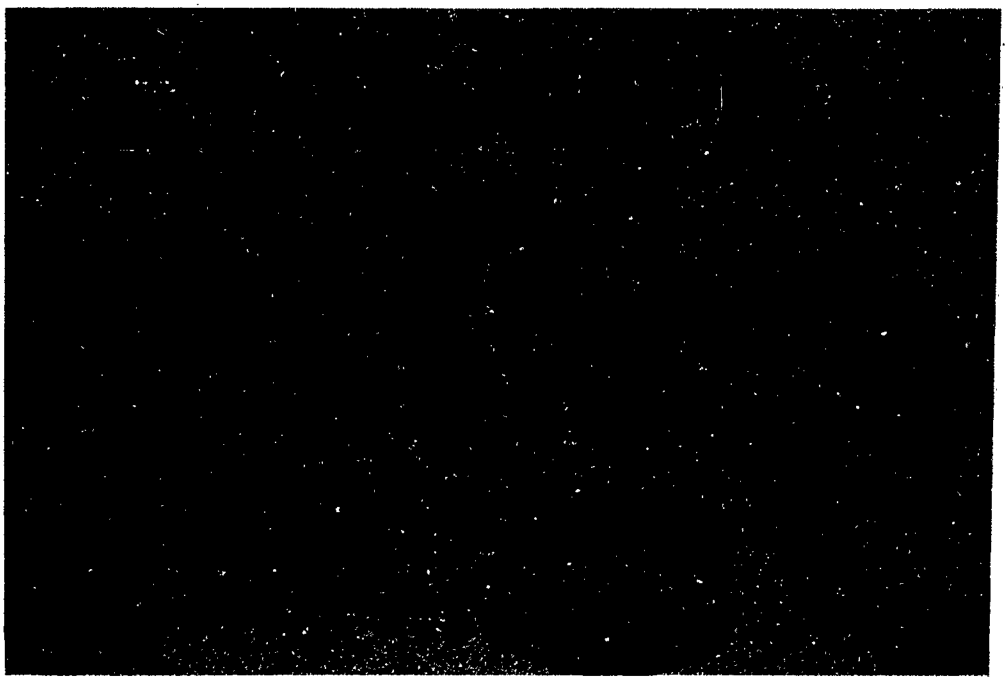

Figure 1.2 The NML skin simulant, unmounted and mounted.

skin simulant and that of the normal simulant behind the gray sateen. The effect of spectral differences is evident in the higher absorptance of the bare simulant and the lower absorptance of the poplin for the 3,000 K black-body radiator of Table 1.1.

The NML skin simulant is fabricated of silica-filled urea formaldehyde. As shown in Figure 1.2, it is a disk 3.8 cm in diameter and 1.0 cm in thickness at the high point of the curved face.

Figure 1.2 shows the simulant mounted in a semicylindrical piece of polyethylene, 8 cm in width and 10 cm in diameter. Firm contact between cloth and skin simulant was achieved by means of springs that held the fabric in tension against the curved surface of the simulant, as illustrated in Figure 1.3. For exposure areas larger than 35 mm in diameter, the simulant was mounted in the semicylinder, because the simulant could not be fabricated in the larger size. The polyethylene in the mount extended the effective area, because its thermal properties are similar to those of the simulant. Only negligible differences in temperature and cloth reaction would result from the inhomogeneity.

A lucite plate was employed to effect positive spacing for small-area and large-area exposures, as illustrated in Figure 1.4. The outer cloth was held with sufficient tension to pull the fabric apart when it lost its strength. Thin aluminum plates with holes of the appropriate diameter were fastened to the outer fabric to serve as apertures. These apertures were used to simulate sources having various irradiating areas. Several apertures are shown in Figure 1.5. Shields were employed to restrict the admission of thermal radiation to the desired portions of the specimens.

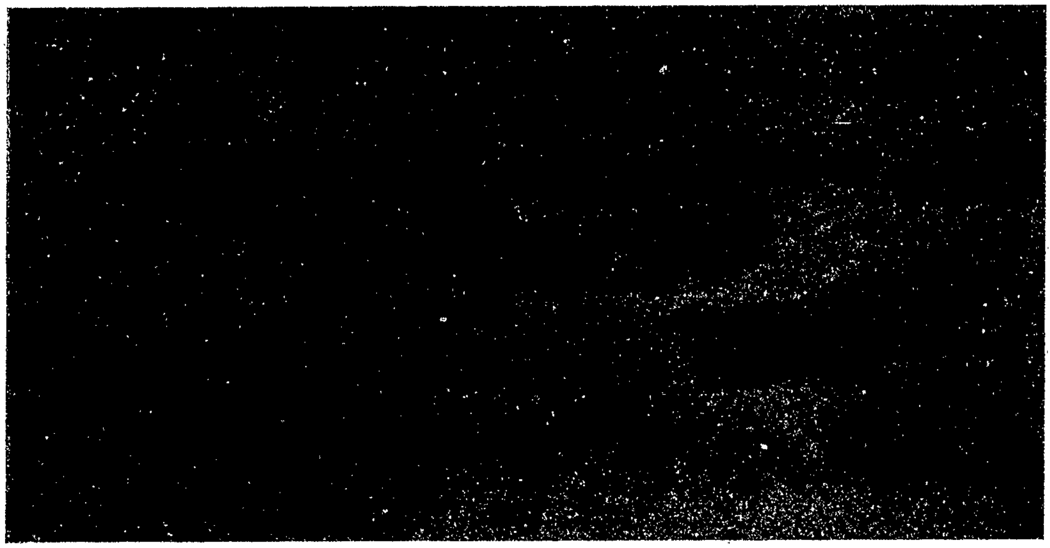

Figure 1.3 Method of mounting fabric assembly in contact with the NML skin simulant.

The temperature rises behind the fabrics in contact are significant and most reproducible at radiant exposures less than those required for charring effects on the cloth. Charring occurs at exposure levels approximately one half those required for igniting the cloth spaced away from the skin simulant. However, because ignition was desired in the spaced configuration and only one station was to be instrumented for each shot, copper screens were employed in the contact situations to allow placement of the spaced and contact assemblies at the same location. The copper screening has a transmission of 0.48. Several cloth contact specimens were exposed without screens, so that appreciable temperatures would occur if the radiant exposure was significantly lower than expected.

At the designed radiant exposure of 15 to 20 cal/cm^2, the spaced configurations were expected to ignite; therefore, precise control of the fabric's moisture content was necessary. All exposure assemblies, therefore, were kept at a minimum moisture content by enclosure of the assemblies in a desiccated chamber. The window material was a thin film of plastic, polyvinylidene chloride (Saran) 0.0005 cm thick with an optical transmission factor of 0.90. The edge of the thin window was blackened and the window kept in tension. The initial phases of the thermal pulse melted the blackened plastic, and the tension removed the window.

Motion-picture cameras, some facing the specimens and others the point of burst, were employed at the recording station during each of the two shots. The cameras were placed in front

Figure 1.4 Method of mounting fabric assembly spaced away from the NML skin simulant.

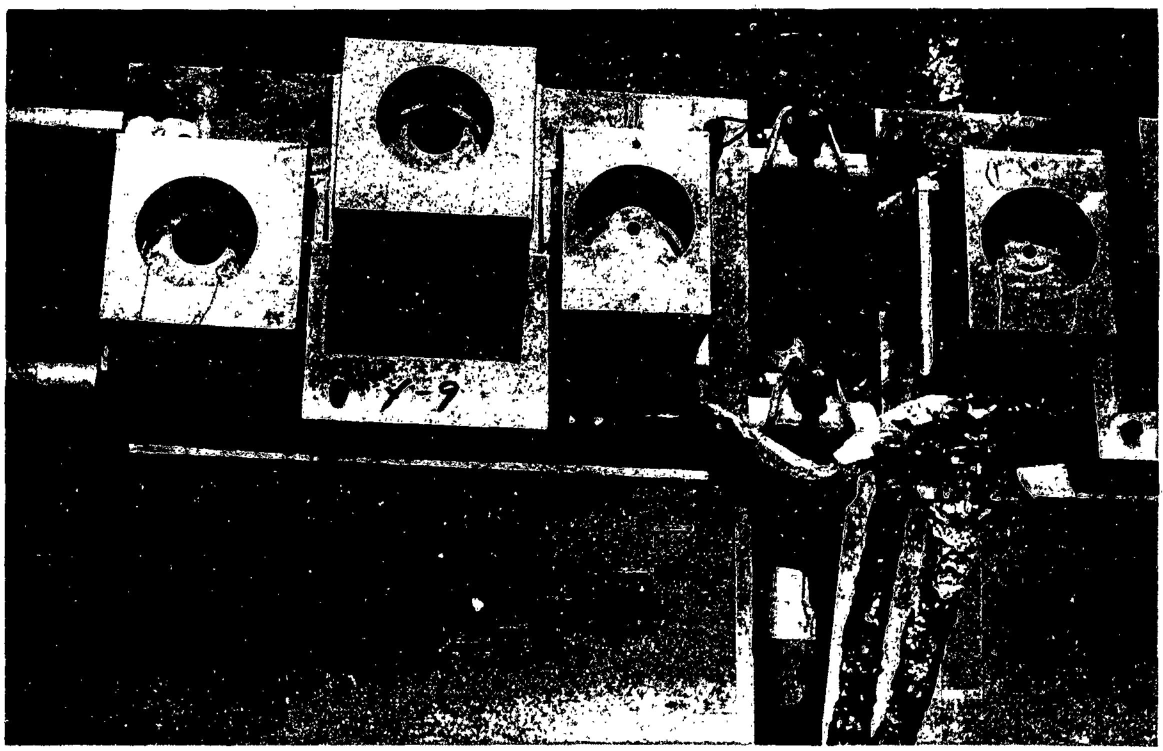

Figure 1.5 Typical skin simulant exposure panel.

of the specimen racks to document the presence of smoke, flame, local obscuration, and other factors.

The six configurations employed in the uniform evaluation study (see second paragraph of this section) were exposed in the laboratory to the carbon-arc thermal-radiation sources, whose irradiance duplicates the generalized nuclear-weapon thermal pulse, which has been normalized in terms of the time for the irradiance to reach its maximum, t_m. Pulses with times to maximum irradiance of 0.2 to 3.2 seconds were employed with corresponding radiant exposures ranging from 4 to 30 cal/cm^2 in terms of equivalent field radiant exposures, Q_f. Because the exposure was terminated at approximately 9 t_m, the laboratory pulse delivered a radiant exposure of 2 $H_m t_m$, where H_m is the maximum irradiance. The appropriate correction was applied to obtain Q_f, the equivalent field radiant exposure, which is given by:

$$Q_f = 2.57\ H_m t_m$$

Exposures have been made to the carbon-arc sources, without an aperture and with apertures of 0.9 and 1.7 cm in diameter, to determine the influence of area of irradiation on the temperature rise of the skin simulant for the six different configurations. The distribution of irradiance in the exposure plane of the carbon-arc source was found to be approximately Gaussian, the irradiance dropping to 90 percent of the irradiance maximum at a radial distance of approximately 0.8 cm.

To extend the study of exposure area to larger areas, a tungsten source employing a bank of tubular lamps was utilized. The area of irradiation was essentially uniform over an area 8 cm in diameter. Since the irradiance was limited to a maximum of 6 cal/cm^2-sec and a variable shutter mechanism was not readily available, square-wave exposures were employed.

DATA REQUIREMENTS

The data required for the validation of laboratory methods of evaluating the protection by uniforms were the maximum temperature rises produced in the skin simulants by the thermal radiation pulse of the nuclear detonation, as well as the radiant exposures and irradiance history at the particular station.

The data were recorded in the form of traces on photographic oscillographic records. The skin simulant's temperature histories were derived from the deflections of the recorded traces by the use of the thermocouple constant (27 C/mv) and the sensitivity (mv/mm) as determined for the actual circuit employed at the respective stations.

The maximum temperature rises thus obtained were compared directly with those predicted from the laboratory exposures. Skin-simulant temperatures were measured in the laboratory for the range of radiant exposures expected in the field test, and the predicted temperatures were selected for the measured radiant exposures. Any differences in the actual temperatures from the predicted values were studied to determine inadequacies in the laboratory evaluation methods.

The influences of a sufficient number of parameters were evaluated in the field to permit conclusions as to those aspects in which the laboratory exposures might fail to duplicate the exposures to a nuclear detonation. It should be possible to determine whether the inadequacy may be attributed to the differences in the spectra of the two sources, in their areas of irradiation, or in their pulse shapes.

Data on the temperature, relative humidity, pressure, and wind direction and velocity were obtained. These data were used in evaluating the validity of the field-test results as they might have been affected by the immediate environment. The presence or absence of dew on the thermal-radiation meter windows, excessive air flow across the specimen, and other effects of the environment could account for significant differences between laboratory and field measurements. Therefore, the indicated meteorological data were obtained in order to evaluate these effects.

RESULTS

Laboratory. The results of experiments conducted in the laboratory were immediately applicable to the analysis of the field data. The various configurations of fabric and skin simulant

were exposed to the carbon-arc source whose output simulated the thermal flux emitted by nuclear detonations.

The temperature rise per unit radiant exposure of the skin simulant, unclothed and with cloth in contact, was determined and is given in Figure 1.6 as a function of the time to maximum irradiance. The temperature rise of the skin simulant was linear with radiant exposure up to the point where the cloth was severely charred.

The maximum temperature rise as a function of radiant exposure for the configuration where the cloth is spaced away from the skin simulant is given in Figure 1.7 for various times to maximum irradiance. The shaded area represents the range of temperatures observed when the

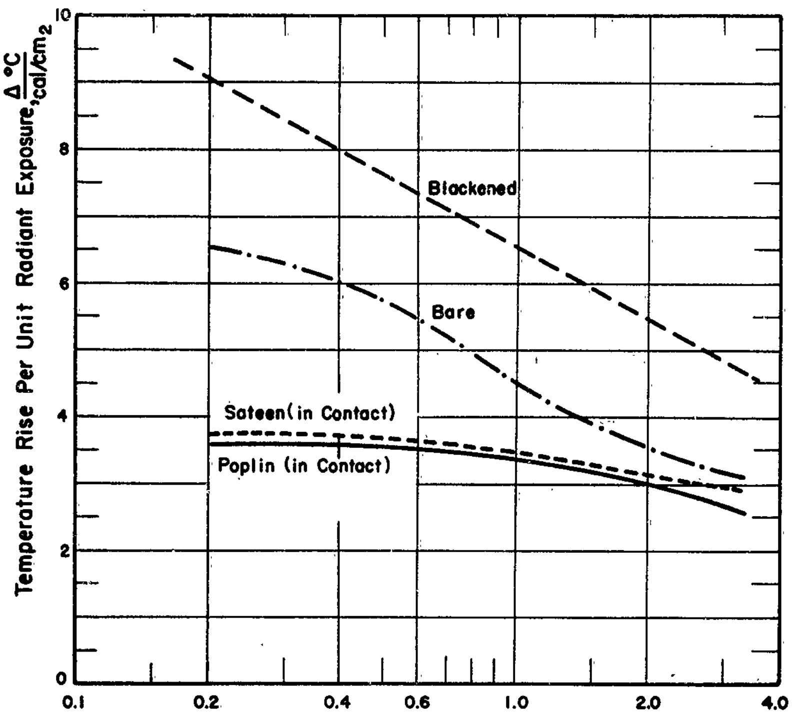

Figure 1.6 Maximum temperature rise of NML skin simulant versus pulse length.

cloth either glowed or flamed. The vertical dashed lines indicate that the sateen ignited at exposures lower than those for the poplin for each given pulse. At low-radiant exposures before the onset of ignition, the various curves run together and the temperatures obtained are independent of the fabric type and the pulse length.

The temperature rises of the skin simulant for the various configurations when exposed to a wide-area tungsten source were measured as a function of the area of exposure. Square-wave exposures were employed; exposure durations were selected to give maximum temperature rises comparable in magnitude and duration to those expected in the field investigation.

For the configuration in which the skin simulant is in contact with the fabric, the temperature maxima of the skin simulant for the 9-mm-diameter area were 15 percent less than for the larger-area exposures. No significant differences were found among the results of the 17-, 35- and 75-mm-diameter exposures.

For the configuration in which the skin simulant is in back of and separated from the fabric system, the temperatures for exposures not resulting in ignition varied for the several aper-

tures, but the differences in temperature are not significant. However, when ignition occurred, the temperatures behind the 9- and 17-mm apertures were usually much lower than those behind the 35- and 75-mm apertures. This was due to the fact that the amount of cloth burned was usually insufficient to result in simulant temperatures normally associated with flaming. In the laboratory the temperature maxima, when the cloth is ignited and either glows or flames, vary between rather wide limits but are usually greater than those associated with second-degree burns. If the glowing or flaming cloths are removed soon after ignition, such temperatures may not occur.

Shot Yellowwood. The maximum temperature rises measured on the skin-simulant specimens exposed to Shot Yellowwood are given in Table 1.2 and are listed in the column marked "Field."

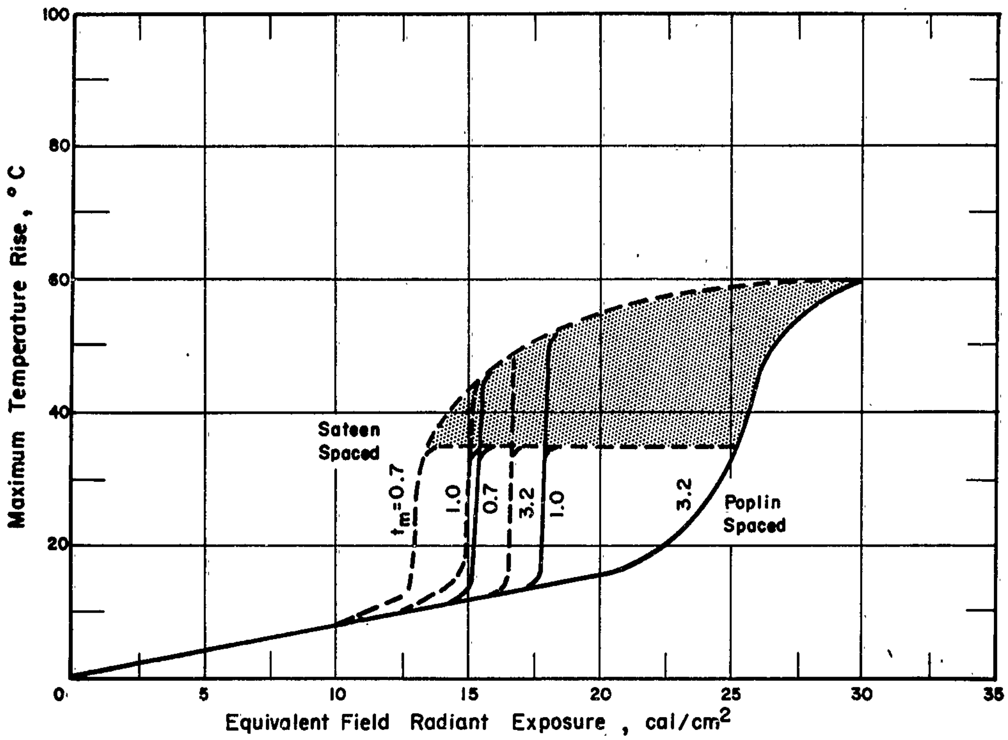

Figure 1.7 Maximum temperature rise of NML skin simulant predicted by laboratory exposures for 0.7, 1.0, and 3.2 seconds, t_m pulse.

There was no evidence of scorch, char, or ignition on the fabrics of the assemblies. The total radiant exposure at the station on Site Olive was 3.3 cal/cm^3, rather than the 20 cal/cm^2 for which the station was planned. The yield of about 400 kt was considerably less than the expected 2.5 Mt and resulted in a t_m of 0.61 second. The details of the thermal measurements are given in Part 2. The irradiance maximum was 2.53 cal/cm^2-sec, and the irradiance history was essentially the same as the generalized pulse (Reference 7) until about 5 or 6 seconds. For longer times, the measured pulse was strongly attenuated. The radiant exposure of the corresponding comparison pulse, therefore, would be 2.57 H_m t_m, or 4.0 cal/cm^2.

The temperatures of the skin-simulant specimens for comparison with the Yellowwood results were accordingly computed, employing a radiant exposure of 4.0 cal/cm^2 and the data for a pulse of 0.61 second, t_m, of Figure 1.6 for the bare, blackened, and contact-clothed simulants. Since the radiant exposure was low and ignition did not occur, the comparison data for the spaced fabrics could be gotten from the common portion of the curves in Figure 1.7, where the temperature

rise is independent of pulse length. For the specimens under the screens, a radiant exposure of 4.0×0.48, or, 1.92 cal/cm^2 was employed.

The differences, in percent, between the laboratory-predicted and the field temperatures are given in Table 1.2 using the laboratory temperatures as the base. The differences for the spaced samples are large in proportion but are not necessarily of importance as differences in assessing laboratory-source adequacy. Two contact specimens, the poplin and sheeting with aperture of 75 mm, and the sateen and sheeting with aperture of 17 mm, gave obviously spurious data, which will not be considered in the analysis.

TABLE 1.2 MAXIMUM TEMPERATURE RISE OF SKIN SIMULANTS, SHOT YELLOWWOOD

Specimen Skin Simulant Covering	Aperture Diameter	Maximum Temperature Rise		Difference
		Laboratory	Field	
	mm	C	C	pct
Uncovered	35*	11.9	10.0	−16
Blackened	9*	13.9	17.3	+24
	35*	13.9	18.0	+30
Poplin and sheeting in contact	9*	5.7	6.2	+9
	17*	6.7	7.2	+7
	17*	6.7	6.8	+1
	35*	6.7	6.4	−4
	35*	6.7	6.8	+1
	75*	6.7	2.6	—
	17	14.0	11.9	−15
	35	14.0	9.1	−35
Sateen and sheeting in contact	9*	5.8	5.8	0
	17*	6.9	10.2	—
	17*	6.9	8.3	+20
	35*	6.9	8.4	+22
	35*	6.9	8.2	+19
	75*	6.9	8.6	+25
	9	10.2	12.2	0
	17	14.4	13.2	−8
	17	14.4	16.3	+13
	35	14.4	14.4	0
Poplin and sheeting spaced 5 mm	17	3.4	2.0	—
	17	3.4	2.6	—
	35	3.4	2.6	—
	75	3.4	2.6	—
Sateen and sheeting spaced 5 mm	9	3.0	1.3	—
	17	3.4	1.2	—
	35	3.4	3.0	—
	75	3.4	2.5	—

* Exposed behind a screen with 0.48 transmission.

The temperature history of each field specimen was normalized with respect to its own maximum temperature rise, given in Table 1.2. The resulting curves are plotted in Figure 1.8 for the uncovered skin simulants, and in Figures 1.9 and 1.10 for the fabric assemblies in contact with the skin simulant. The temperature histories of all the clothed specimens with the 17-mm and 35-mm apertures fell within the restricted ranges indicated by the shaded areas in Figures 1.9 and 1.10.

The free-air surface temperature at Yellowwood detonation time, 1400 hours, was 87 F, and the relative humidity was 63 percent. The wind velocity was 14 knots at 90 degrees, almost di-

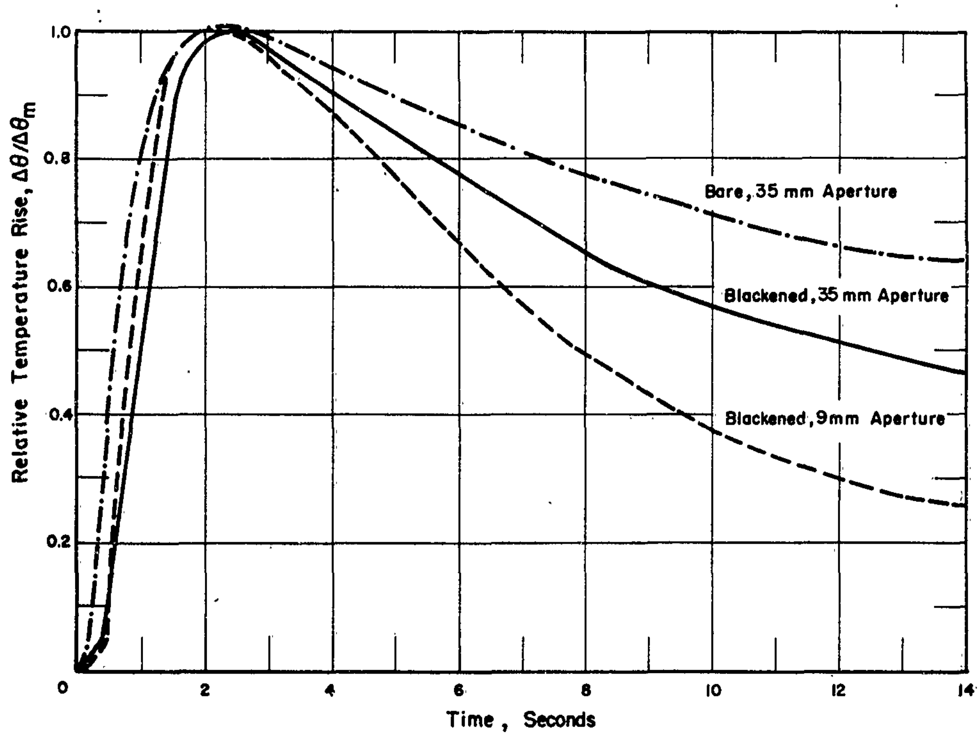

Figure 1.8 Temperature histories of the NML simulant, bare, and blackened.

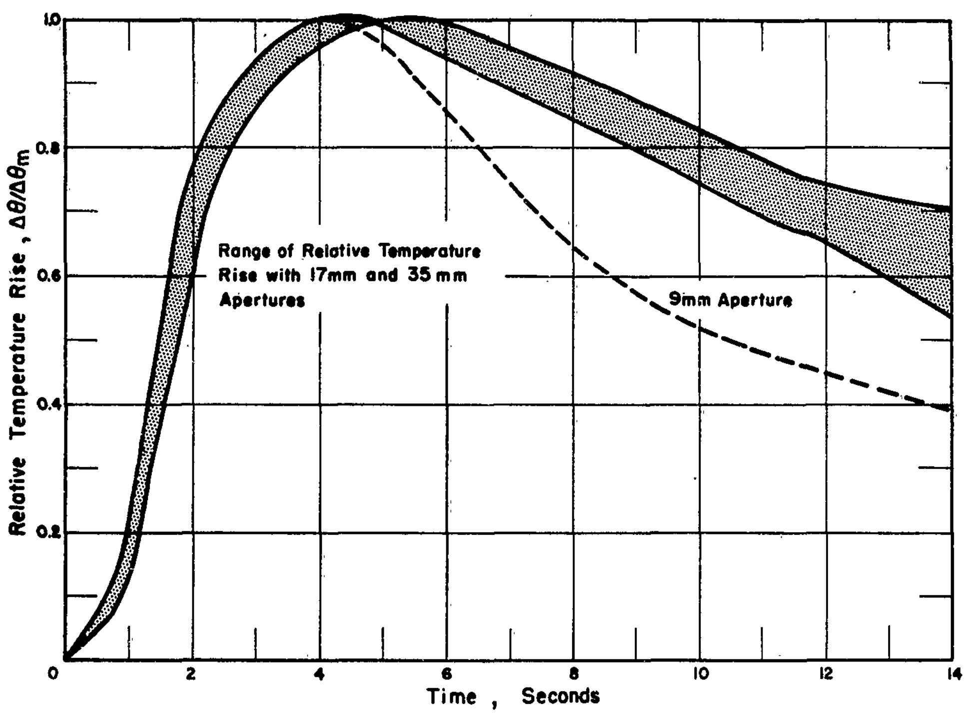

Figure 1.9 Temperature histories of the NML simulant in contact with the poplin assembly.

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rectly behind the specimens. The air temperature was well above the dew point of 73 F. No corrections were considered necessary for correlation to normal laboratory exposures.

Shot Walnut. The maximum skin-simulant temperature rises measured in Shot Walnut are listed in Table 1.3 in the column marked "Field." Postshot examination of the fabrics revealed no visible effects on the assemblies exposed under the neutral screens. For the unattenuated

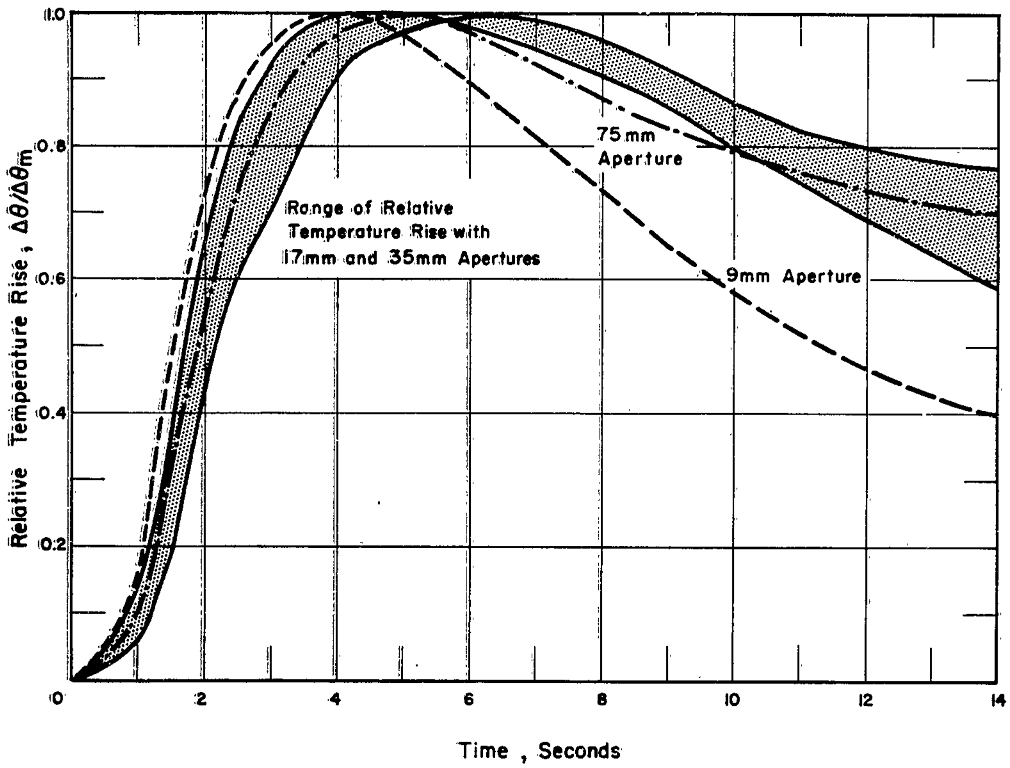

Figure 1.10 Temperature histories of the NML simulant in contact with the sateen assembly.

exposures, the poplin assemblies were heavily scorched but not charred in the contact configurations but were severely charred and apparently close to ignition temperature in the spaced configurations. The sateen assemblies were also severely scorched in the contact configurations, but in the spaced configurations, both the sateen and sheeting were apparently consumed by combustion, or nearly so, and the remainder presumably removed by the blast at 15.9 seconds after the initial thermal pulse.

Shot Walnut gave a yield of 1.45 Mt. At the station on Site Olive, the total radiant flux measured was 14.7 cal/cm^2, the thermal pulse having its irradiance maximum at 1.19 seconds with a magnitude of 6.3 cal/cm^2-sec. The thermal pulse was prematurely obscured, and the corresponding comparison pulse would have a radiant pulse of 2.57 $H_m t_m$, or 19.3 cal/cm^2.

The laboratory temperature rises of the skin simulant corresponding to the Walnut data were computed using the data of Figure 1.6 for the contact configurations and those of Figure 1.7 for the spaced configurations, assuming a pulse whose t_m was 1.19 seconds and a radiant exposure of 19.3 cal/cm^2. For the specimens under screens, a radiant exposure of 19.3 × 0.48, or 9.25 cal/cm^2, was employed.

The purpose of exposing the various specimens without attenuation was primarily for assuring quantitative data in the event that the radiant exposure received at the station was much less than that expected for the design yield. The actual temperature rises of these specimens were

greatly in excess of those corresponding to the third-degree-burn level; since these were of minor interest and not as well documented as those for the exposures behind screens, they were not considered in analyzing the results.

The free-air surface temperature at Walnut detonation time, 0630 hours, was 80.8 F, and the relative humidity was 84 percent. The wind velocity was 17 knots at 90 degrees, almost directly behind the specimens. The temperature was above the dew point of 76 F. No corrections are considered necessary for correlation to normal laboratory exposures.

TABLE 1.3 MAXIMUM TEMPERATURE RISE OF SKIN SIMULANTS, SHOT WALNUT

Specimen Skin Simulant Covering	Aperture Diameter	Maximum Temperature Rise: Laboratory	Maximum Temperature Rise: Field	Difference
	mm	C	C	pct
Uncovered	35*	39.0	38.7	−1
Blackened	9*	58	61.1	+5
	35*	58	60.8	+5
Poplin and sheeting in contact	9*	26.1	23.4	−10
	17*	30.7	26.6	−13
	17*	30.7	27.3	−11
	35*	30.7	30.3	−1
	35*	30.7	27.3	−11
	75*	30.7	28.9	−6
	17	64.0	52.0	−19
	35	64.0	55.9	−13
	35	64.0	44.5	−30.5
Sateen and sheeting in contact	9*	27.1	27.2	+0.4
	17*	31.9	35.5	+11
	17*	31.9	32.4	+1.5
	35*	31.9	34.8	+9
	35*	31.9	31.8	−0.3
	75*	31.9	32.7	+2.5
	9	56.5	47.7	−15.5
	17	66	57.8	−13
	17	66.5	60.3	−9
	35	66.5	61.4	−7.5
Poplin and sheeting in spaced 5 mm	17	8	5.2	—
	17	30	11.7	—
	75	>30	13.1	—
Sateen and sheeting spaced 5 mm	9	20	47.5	—
	17	30	49.7	—
	35	>30	89	—
	75	>30	42.1	—

* Exposed behind a screen with 0.48 transmission.

DISCUSSION

Data Reliability. The reproducibility in the laboratory of the maximum skin-simulant temperatures is within 10 percent of the values given in Figures 1.6 and 1.7. The reproducibility was determined by comparison of results from similar specimens obtained over a period of several years, employing several carbon-arc sources and pulse mechanisms. The largest source of error stems from the variations in the shape of the thermal pulse actually delivered. Most of the laboratory exposures are for the temperature range of interest in burn studies,

namely, 15 to 30 C; therefore, the comparison with the field exposures to Shot Yellowwood was not made at the optimum level.

While the radiant exposure at the Yellowwood study station was unexpectedly low, the deflections on the oscillograph traces were large enough to keep the reading error to within 3 percent. Inspection of the temperature histories of the skin-simulant specimens plotted in Figures 1.8 and 1.9 shows that in all exposures the maximum temperatures for Shot Yellowwood occurred within the first 6 seconds and prior to any significant departure of the field irradiance history from the generalized pulse as shown from inspection of Figure 2.5.

The radiant exposure received at the station for Shot Walnut was sufficient to generate data in the region of interest. All of the oscillograph traces appeared to be proper and showed sufficient deflection to render reading errors negligible.

Correlation with Laboratory Data. While the indiscriminate average of the differences between field and laboratory temperatures was small, systematic differences were obtained among the various types of assemblies. If the results for the lower (screened) radiant exposure for Shot Yellowwood are discounted as being lower than the main level of interest and the results

TABLE 1.4 SUMMARY OF CORRELATION OF LABORATORY AND FIELD TEMPERATURES

Differences are given in terms of laboratory values.

Specimen	Shot Yellowwood	Shot Walnut
	pct	pct
9mm/17mm	<5	<5
17/35mm	<5	<5
Blackened	+27	+5
Sateen, contact	+17	+4
Bare	−16	−1
Poplin, contact	−25	−8

for the (unscreened) contact cloths for Shot Walnut are discounted as being much above the level of interest, the pattern shown in Table 1.4 is established. The temperatures measured for the spectrally neutral specimens, the blackened simulant and the sateen in the contact configuration are 22 percent high for Shot Yellowwood and 5 percent high for Shot Walnut. The uncertainty in irradiance maximum for Shot Yellowwood, as indicated by the 95-percent-confidence interval, was 10 percent, leaving a discrepancy in temperatures of at least 12 percent.

The conclusion to be drawn from the temperatures of the spectrally neutral specimens is that the present laboratory methods yield temperatures correct to about 15 percent and are generally lower.

The empirical relationship developed in the laboratory to express the dependence of temperature rise on area of exposure holds in the field to within 5 percent; consequently, laboratory methods are adequate for determining area effects.

The temperatures behind the poplin assemblies were measurably less than those behind the spectrally neutral samples. This discrepancy between laboratory predictions and field results can readily be explained by the fact that the effective radiating temperatures of Shots Walnut and Yellowwood, as deduced in Part 2, were lower than that of the laboratory carbon-arc source. The higher relative infrared content of the field sources would cause lower temperatures since the fabric reflects infrared energy more than it does energy of shorter wave lengths. The results of exposures to laboratory sources, therefore, must be corrected for spectrum when employed in predicting effects due to surface detonations.

During Shot Walnut, the sateen assemblies in the spaced configurations ignited, and the temperatures were higher than those which were obtained in similar situations during Operation Plumbbob. This is probably due to the fact that the greater distance to point of burst during Operation Hardtack (resulting in later arrival of the shock wave) allowed the ignition to proceed

farther before being extinguished. The configuration with the 35-mm aperture had a flame or glow which apparently survived the arrival of the shock wave and resulted in an excessively high temperature rise in the simulant. In the laboratory, where no attempt has yet been made to simulate the shock wave, temperature rises of this magnitude have been noted when ignition occurs.

The poplin assemblies in the spaced configurations during Shot Walnut did not ignite, but they were deeply charred and were probably close to ignition. The radiant exposure, however, was measured to be 10 percent higher than required for ignition in the laboratory. The Walnut fireball had a radiating temperature lower than that of the laboratory carbon-arc source. Hence, the hot-wet (poplin) uniform would have a lower radiant absorptance in the field and would require higher radiant exposure for ignition.

The lower temperatures were observed for the 9-mm contact assemblies, as predicted.

For the sateen assemblies in the spaced configurations, the field temperatures showed a lack of dependence on area. This is unimportant in assessing the adequacy of area of irradiation afforded by the laboratory source, because occurrence of ignition is, alone, a sufficient criterion for burn prediction.

CONCLUSIONS

Laboratory exposures of representative burn situations, employing a skin simulant and a large-area, thermal-radiation source, have predicted the dependence on area of the thermal radiant flux required to cause characteristic damage noted in the field. The results of the field exposures were within 5 percent of the area dependence predicted from laboratory studies and well within the experimental error of about 10 percent.

The pulse shape (or time variation of irradiance) of the laboratory carbon-arc thermal pulse was shown to be adequate to within 15 percent. It was demonstrated that, in correlating laboratory and field data, allowance must be made for differences in the pulses. In the laboratory, some pulses have a "tail" energy, which in the field under ideal conditions, e.g., an air burst measured outside the blast zone, contributes significantly to the total radiant exposure but does not contribute appreciably to material damage. Again, in the field a given pulse may be terminated by obscuration of the fireball produced by the arrival of the blast wave or by the Wilson cloud, whereas the laboratory pulse simulating the generalized field pulse includes significant tail energy. Since the time variations of irradiance for Shots Yellowwood and Walnut, as measured at Site Olive, confirm the predictions of the generalized field pulse, the 15 percent disagreement between laboratory and field data must be ascribed to (1) experimental error, (2) the small differences between the actual pulse delivered in the field and the generalized pulse, or (3) the small differences between the laboratory pulse and the generalized pulse.

The effect of different source spectrum was seen in the skin-simulant temperatures for the hot-wet (poplin) fabric system for both shots. The simulant temperatures were lower by approximately the amount predicted from spectrophotometric measurements for the lower radiating temperature of the surface detonations.

RECOMMENDATIONS

The study of laboratory-to-field correlation of thermal-radiation effects indicated a reasonable ability to predict results in the field, under controlled conditions. In order to produce, in the laboratory, the effects to be expected in the field, it is necessary to meet the following two requirements. First, the irradiance history must be as closely approximated as the type of effect warrants. For example, for unclothed simulants, the temperature history was shown to be strongly dependent on t_m while for the clothed situations the temperature rise is less dependent on pulse length, except in the case of ignition of the fabric. Second, the radiant exposure actually delivered in the situation being simulated should be accounted for in making predictions. Although in many instances the latter portions of the pulse are ineffectual, the tail energy is usually sizable. To avoid ambiguity, the results should include a statement indicating whether the tail energy was included in the radiant exposure value. Because the generalized

field pulse contains the tail energy, it is desirable to specify an effect in terms of the radiant exposure for a generalized field pulse.

Additional important areas in the prediction of thermal-radiation effects and of protection afforded by uniforms were not covered; however, they deserve further consideration in laboratory studies as well as in laboratory-to-field correlation studies. Among the parameters for which suitable quantitative information is lacking are: (1) effects on specimens larger than 3 inches in any extent; (2) interaction of thermal radiation and blast effects; (3) effects on various geometrical configurations; and (4) evasive action, or time at which the effect occurs.

Part 2
BASIC THERMAL-RADIATION MEASUREMENTS

OBJECTIVE

The purpose of the thermal-radiation measurements was to document the radiant exposure and the time variation of irradiance at the stations employed in the skin-simulant studies.

BACKGROUND AND THEORY

In order to draw quantitative conclusions from a study of thermal effects during a full-scale, nuclear-test operation, it is essential to determine the radiant exposure and variation of irradiance with time at the thermal-effect stations. Because of possible partial obscuration by clouds and other local disturbances, measurements of radiant exposure are desirable at the individual stations.

The exposure was measured with calorimeters and a radiometer similar to those which have been used by NML and the U. S. Naval Radiological Defense Laboratory (NRDL) in previous operations. The recording copper-disk calorimeter (button calorimeter) consists essentially of a blackened copper disk, approximately 1 cm in diameter, to which a thermocouple is attached. The radiant exposure is computed directly from the temperature history of the button, with corrections for the losses occurring during an exposure. The radiometer is a thin, blackened, constantan-foil receiver soldered over a small hole in a copper-block heat sink. A fine copper or iron wire, attached to the back of the foil in the center of the hole in the heat sink, allows the recording of the foil temperature, which is proportional to the irradiance.

For an additional measurement, one of the self-contained calorimeters developed at NML was employed for each shot. The instrument was modified to include a thermocouple and to operate on essentially the same principles as the copper-disk calorimeter. The design features of this instrument, called the thermal-radiant-exposure meter (TREM), afforded greater flexibility and permitted fabrication of a series of units covering a much wider range of radiant exposures than heretofore possible and with a finer resolution throughout the range. It is also called a plate calorimeter. The essential part of the meter was a copper plate of uniform thickness, blackened on one face (upon which the radiation would be incident). Against the other face was placed, in point contact, a series of pellets with precise melting temperatures. A thermocouple was soldered to the back of the plate and connected to the recorder. The pellets were obtainable over a wide range of temperatures at intervals of approximately 7 C. As shown in Figure 2.1, this assembly was housed in an airtight box containing a quartz window to admit radiation. A reading was taken after exposure by observing the last in the series of pellets to have melted at the point of contact with the copper plate. Laboratory calibrations of the TREM indicated that the temperature of the copper plate could be computed from the physical parameters by the use of the measured loss rates. The various components of the meter are shown in Figure 2.2. Typical melts on pellets after exposure are shown in Figure 2.3.

OPERATIONS

The thermal radiation was measured during Shots Yellowwood and Walnut at the station employed for the skin-simulant studies. The instruments were mounted and connected and the circuits were calibrated several days before each shot. The circuits were connected to the timing lines the day before a particular shot was announced as ready for firing. The oscillo-

graph records were recovered several hours after the shot and were developed the same day and analyzed.

INSTRUMENTATION

For both shots, the thermal radiation at the skin-simulant stations was measured with five button calorimeters, one plate calorimeter (TREM), and one radiometer mounted on the panels with the skin-simulant specimens and connected to the same oscillographs as the skin-simulant

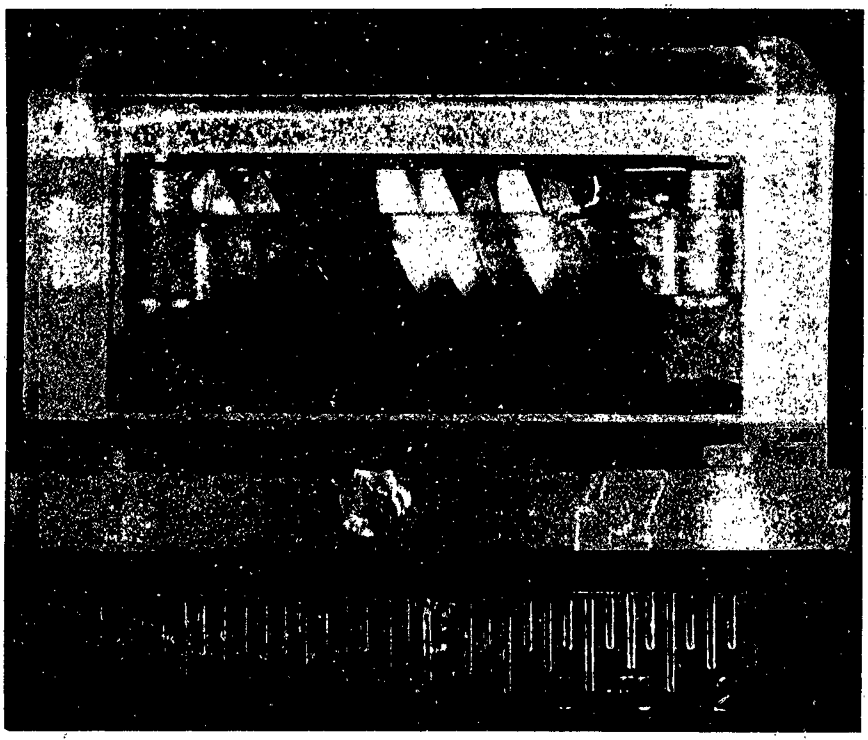

Figure 2.1 The NML thermal radiant exposure meter.

thermocouples. Apertures were placed in front of the buttons of several of the calorimeters, to eliminate the possibility of energy falling on the side of the button or anywhere behind the button. The angles of view of the instruments varied, ranging from about 82 to 111 degrees.

The sensitivities, cal/cm^2-mv, for the NML instruments were derived from the mass of the buttons or thickness of the receiver plates, the specific heat of copper, the thermocouple calibration, the absorptivity, and the aperture, or exposed area. These constants have been checked in the laboratory many times by repeated exposures of different combinations of the parameters involved. The calibration of the calorimeters and radiometers obtained from NRDL were checked at NML by exposures to the carbon-arc thermal source. It was found that the sensitivities quoted by NRDL were lower than those obtained by cross-calibration with the NML instruments. The radiant exposures listed in this report for those instruments are, accordingly, 1.19 times higher than if the original constants were employed.

DATA REQUIREMENTS

The data required for the basic thermal-radiation measurements include the sensitivity constants of the various instruments, as obtained from fabrication details and laboratory measurements, and the circuit calibration from the measurements made in the field. The data were

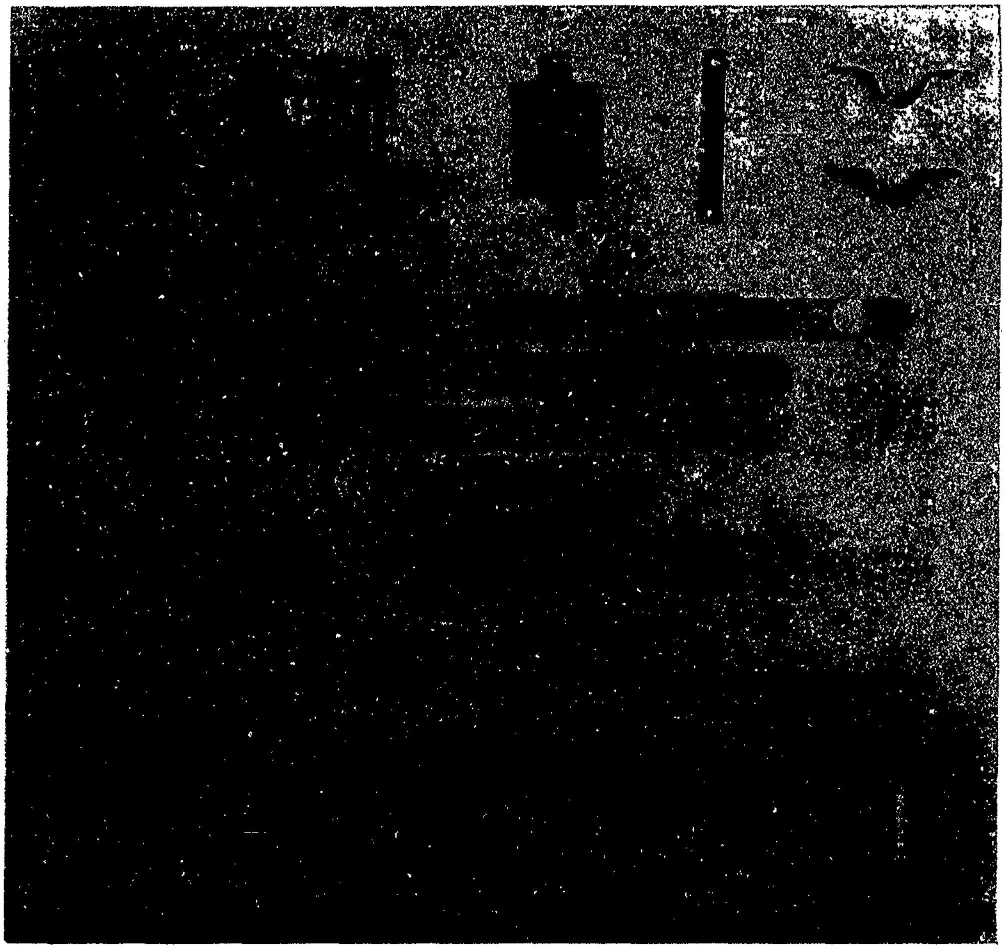

Figure 2.2 Components of the NML thermal radiant exposure meter.

Figure 2.3 Melted pellets from an exposed thermal radiation exposure meter.

obtained in the form of photographic oscillograph records. These records were developed and the data analyzed shortly after each shot.

Information was required on the actual point of burst, to determine the necessity for, and the amount of, correction to be made because of the resulting misalignment. The results were interpreted by means of motion pictures, obtained from cameras located at the station, which documented the presence of obscuration and the approximate size and uniformity of the radiating area.

RESULTS

Shot Yellowwood. The thermal-radiation measurements for Shot Yellowwood are summarized in Table 2.1. The radiant exposures listed for the calorimeters were obtained by computing the

TABLE 2.1 THERMAL RADIATION, SHOT YELLOWWOOD

Instrument	Radiant Exposure	Irradiance	Time to Second Maximum
	cal/cm^2	cal/cm^2-sec	sec
Plate Calorimeter NML No. 32-10	3.25	2.62	0.63
Button Calorimeter NML No. 4*	3.36	—	—
Foil Radiometer NRDL No. 10-152	3.21	2.53	0.60
Button Calorimeter NRDL No. BK-250	3.28†	—	—
Button Calorimeter NML No. 10*	3.20	—	—
Button Calorimeter NRDL No. WH-170	3.16	—	—
Button Calorimeter NML No. 14*	3.42†	2.43	0.60
Average	3.27	2.53	0.61
95-pct confidence	0.09	0.24	0.04

* With 5-mm aperture.

† Corrected for screen transmission and extra quartz window (0.48 × 0.93 = 0.447).

loss corrections for the curves; the irradiance maximum and time to maximum for the plate calorimeter were read from a smoothed curve drawn of the increments of the radiant exposure as a function of time. The button calorimeters had deflections which were too small for a study of the increments during this phase of the pulse. The irradiance maximum, as measured by the foil radiometer, and the time to the second maximum were computed directly from the trace deflection. The 95-percent-confidence intervals were computed and are included in the table. Figure 2.4 is a plot of the irradiance readings from the two instruments as a function of time, with the values normalized to an irradiance maximum of 2.53 cal/cm^2-sec and a time to maximum of 0.61 second.

The correspondence between the irradiance history and the generalized pulse, as given in Figure 2.4, is good to at least 4 times t_m. However, the relationship between the total radiant exposure, irradiance maximum and time to maximum, $Q/H_m t_m$, is 2.12, which is less than the comparison pulse by 21 percent. A plot of the smoothed irradiances in the decaying phase of the pulse, Figure 2.5, reveals that little thermal energy arrived at the station after 9 to 10

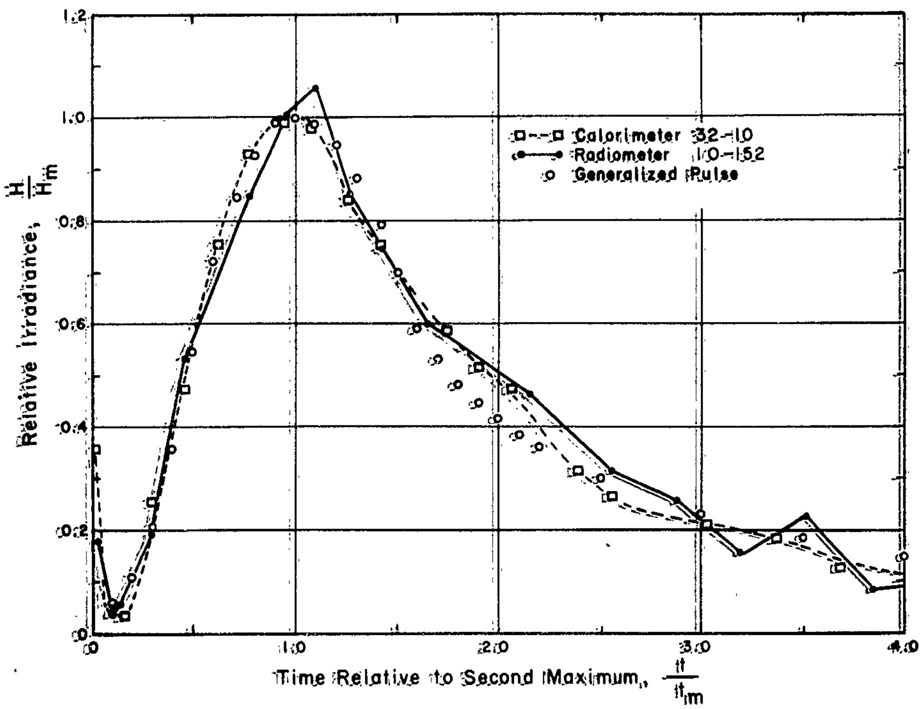

Figure 2.4 Irradiance history of Shot Yellowwood.

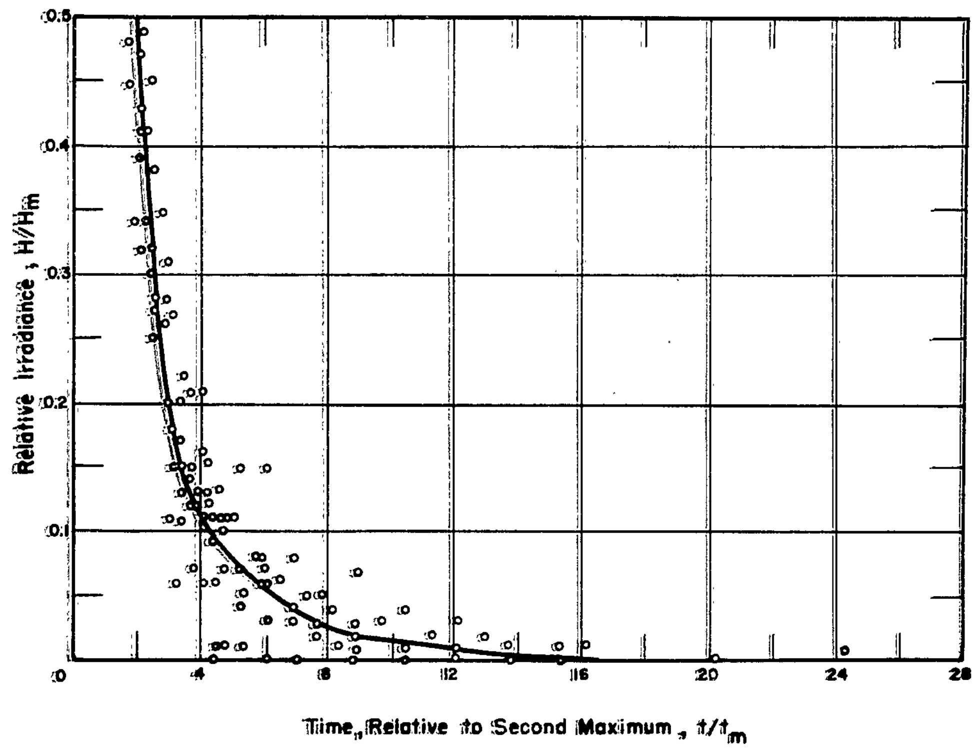

Figure 2.5 Decay portion of irradiance history, Shot Yellowwood.

times t_m. The irradiance from the fireball was effectively cut off at this time by the formation of the condensation cloud. The evidence of obscuration furnished by the calorimeters was confirmed by the subsequent examination of the motion pictures taken of the Yellowwood fireball. A clear view was obtained of the fireball until approximately 7.5 t_m, when the cloud, which started to form above the fireball at approximately 6.5 seconds obscured the top of the radiating hemisphere. The cloud grew steadily until at approximately 10 t_m the entire firefall was obscured.

The radiant exposure which would have been delivered if there had been no such obscuration would have been 4.0 cal/cm^2, summing up contributions from the tail out to infinity.

There were no significant differences among the values recorded by the instruments with apertures or screens and those without apertures or screens.

TABLE 2.2 THERMAL RADIATION, SHOT WALNUT

Instrument	Radiant Exposure	Irradiance	Time to Second Maximum
	cal/cm^2	cal/cm^2-sec	sec
Plate Calorimeter NML No. 32-10	14.6	6.4	1.2
Button Calorimeter NML No. 4	15.1	6.8	1.18
Foil Radiometer NRDL No. 10-152	14.7	6.5	1.16
Button Calorimeter NRDL BK-250	15.8	6.6	1.17
Button Calorimeter NRDL WH-170*	13.8	5.8	1.19
Button Calorimeter NML No. 10*	14.8	6.4	1.21
Button Calorimeter NML No. 14	14.0†	5.9	1.21
Average	14.7	6.3	1.19
95-pct confidence	0.62	0.34	0.017

* With 5-mm aperture.

† Corrected for screen transmission and extra quartz window (0.48 × 0.93 = 0.447).

Shot Walnut. The thermal-radiation measurements for Shot Walnut are summarized in Table 2.2. The deflections were large enough to allow reasonably accurate determination of irradiance and time to maximum for the traces of all instruments. Figure 2.6 is a plot of the irradiance history of the main phase of the pulse, and Figure 2.7 shows the tail or latter phases of the thermal pulse.

The relationship between the total radiant exposure, irradiance maximum and time to maximum ($Q/H_m t_m$) is 1.96, which is smaller than that obtained from Shot Yellowwood and 27 percent less than the comparison pulse. Here, even more than in Shot Yellowwood, the irradiance was cut off prematurely. The radiant exposure which would have been delivered if the fireball had not been obscured is 2.57/1.96 times 14.7, or 19.3.

There were no significant differences among the values recorded by the instruments with apertures or screens and those without apertures or screens.

The maximum temperature obtained from examination of the melted pellets in the plate calo-

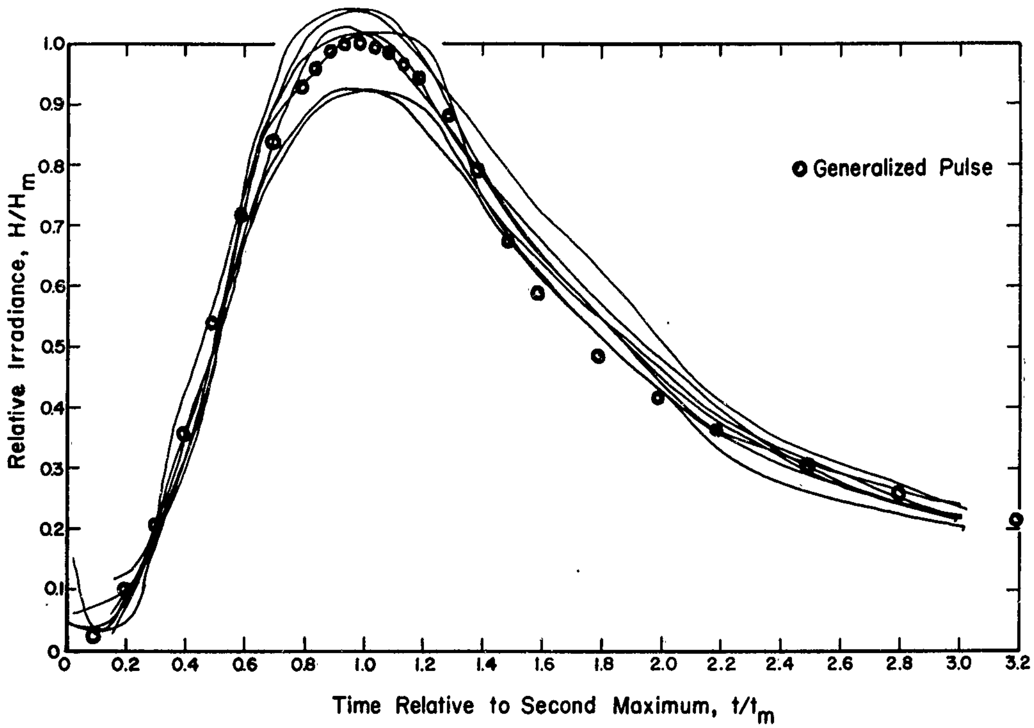

Figure 2.6 Irradiance history of Shot Walnut.

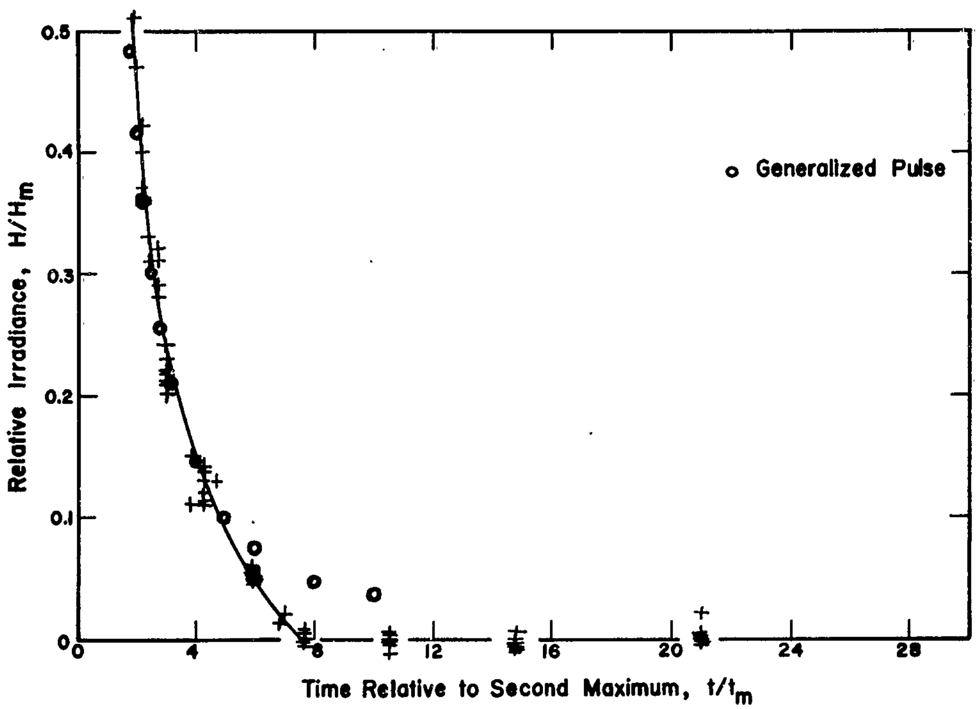

Figure 2.7 Decay portion of irradiance history, Shot Walnut.

rimeter, in conjunction with the ambient temperature at shot time and a calibration constant based upon an idealized pulse, yielded a radiant exposure of 18.3 cal/cm^2.

The thermal pulse for Shot Walnut corresponded closely to the generalized pulse to about 3 times t_m as shown in Figure 2.6. Figure 2.7, however, shows the discrepancy between the two pulses in the later phases, the delivered pulse being effectively terminated at approximately 8 t_m.

The motion pictures of the Walnut fireball showed no definition after approximately the first thirty frames (0.5 second). This was due to the thermal destruction of the filters employed over the lens. Nevertheless it is reasonable to assume the evolution of a cloud in a manner similar to that of Shot Yellowwood, resulting in severe attenuation after about 8 t_m to 10 t_m.

DISCUSSION

The calibrations of the calorimeters used in the two shots are accurate to within 5 percent. All the deflections obtained from these instruments were regular and sufficiently large so that the reading errors associated with radiant exposure measurements were within 3 percent.

The 95 percent confidence computed for the Yellowwood and Walnut results range from 10 percent for the irradiance of Shot Yellowwood to 1 percent for the time to maximum for Shot Walnut.

The effective radiating temperatures of the fireballs were computed, employing scaling relationships for the radius of the radiating hemisphere at the second maximum, a transmission factor of 0.85 per mile, and the measured maximum irradiance. The radiating temperatures of 4,720 K for Shot Yellowwood and 4,440 K for Shot Walnut were less than the temperature of 6,000 K often employed to characterize the spectrum of the carbon-arc source. The difference between the effective radiating temperatures for these surface detonations and that for the carbon-arc laboratory source will in most cases produce measurable differences in the ability of the radiant exposures to cause thermal effects on selectively absorbing materials.

CONCLUSIONS

The measurements of radiant exposure and irradiance obtained by the calorimeters were reasonably consistent with each other and with the physical situation. These values provided a firm basis for the evaluation of the skin-simulant results. The irradiance histories obtained on Site Olive for Shots Yellowwood and Walnut were reasonably close to the generalized pulse up to the time of obscuration by the condensation cloud. The use of the generalized pulse as a reference gave a firm basis for comparison of results obtained with thermal-radiation pulses with differing histories in the final phases.

RECOMMENDATIONS

Future quantitative experiments on effects of thermal radiation should incorporate instruments capable of measuring the irradiance histories in selected spectral regions. Camera-type instruments employed to document the fireball aspect should respond to a wider range of irradiances and should incorporate selective spectral filters.

Part 3
MEASUREMENT of THERMAL RADIATION from VERY-HIGH-ALTITUDE DETONATIONS

OBJECTIVES

The primary purpose was to measure the radiant exposure and irradiance history near the earth's surface during very-high-altitude detonations. One of the objectives was to document the thermal radiation for the retinal-burn studies of Project 4.1. In addition, some skin simulants were exposed on Johnston Island to assess the burn hazard to personnel.

BACKGROUND AND THEORY

The thermal radiation from nuclear detonations at very-high altitudes in relatively low air densities was expected to be of brief duration with characteristics much different from those of low-altitude bursts. The short time of dissipation of the large amount of energy would result in high intensities and a danger of retinal burns in the relatively large area within which the burst could be viewed.

The highest nuclear detonation prior to Shots Teak and Orange was Shot Yucca, a 1.7-kt detonation at 88,000 feet. The results from this detonation indicated a greater portion of energy dissipated as thermal radiation, definitely shorter emitting times, and the presence of more than two radiance maxima. Shots Teak and Orange, detonated in relatively rare atmospheres, were, therefore, expected to involve the dissipation of a large portion of the energy as thermal radiation in very short times.

Because of the high altitude and high radiance (cal/cm^2 sec-ster), the detonations would be visible and constitute a potential retinal-burn hazard at distances of approximately 400 to 700 miles, the distance at which the horizon would obscure the detonation points.

Retinal burns can be expected to occur at lower radiant exposures than skin burns, (Reference 8), because of the focusing properties of the eye. The radiant exposure to cause retinal burns is a function of the irradiance at the eye and the fireball (or source) size and spectral history; stated differently it is a function of the radiance and spectral history of the source. Until the eye is far enough away from a source so that the image of the source on the retina is small enough to be independent of the source size, the irradiance of the image is independent of the distance except for atmospheric attenuation.

No data were available for skin burns or temperature history of skin for the short pulse of thermal energy expected. Several skin simulants were exposed to determine, if possible, the temperature histories which would result from such detonations.

The radiant exposure, Q, from a nuclear detonation with W megatons of thermal energy at a slant distance of D nautical miles may be computed from:

$$Q\ (\text{cal/cm}^2) = \frac{10^{15}\ W\ T}{4\ \pi\ D^2} \times \frac{1}{3.44 \times 10^{10}} = \frac{2{,}320\ W\ T}{D^2}$$

where T is the transmittance of the path considered. For a low-altitude burst, the times of maximum irradiance have been found to be dependent on the yield; for a high-altitude event, however, the air density plays a large role in determining the times of thermal dissipation by radiation, and the pulse length will be dependent on altitude.

The radiance, R , of the fireball may be computed from the irradiance, H , at a distance, D ; the projected area, A , of the fireball; and the path transmittance, T : R (cal/cm^2-sec-ster) = HD^2/TA .

INSTRUMENTATION

Five stations were instrumented for the two shots, one on Johnston Island, three on surface vessels stationed approximately 75, 150 and 300 miles from the island, and one in an aircraft 300 miles from the island. The skin simulants were located only at the Johnston Island station. Figure 3.1 is a photograph of the Johnston Island station.

Two essentially different types of instruments were employed for the measurement of the characteristics of the thermal radiation. One was the black-body or nonselective receiver type,

Figure 3.1 Photograph of Johnston Island station.

including the button calorimeter designed and constructed by NRDL and similar units constructed at NML (see Part 2, Background and Theory). Additional instruments of the nonselective type were designed and constructed at NML to have higher sensitivities and faster response times than the standard button calorimeters. These radiant exposure meters consisted essentially of a thin blackened copper plate or foil with a constantan-thermocouple wire soldered or pressed against the back. These instruments were employed successfully in Operation Plumbbob and in the first phase of Hardtack as a recording and check version of the nonrecording pellet radiant exposure meter.

The other type was the spectrally selective photovoltaic cell, specifically the silicon solar cell. These cells are sensitive to radiation with wave lengths between 450 to 1,000 mμ with a peak sensitivity at 800 mμ. Neutral filters of aluminized glass, exposed and developed photographic film, and wire mesh were employed with these cells.

The calorimeters were calibrated in two ways. For the NML calorimeters and the radiant exposure meters having copper plates 0.010 cm or more thick, the sensitivity of the meter was determined from the unit's dimensions and physical properties. The NRDL calorimeters and

the thin-plate (0.0025 to 0.0065 cm) radiant exposure meters were cross-checked in the laboratory with other instruments.

The linearity, relative sensitivity, and time response characteristics of the photovoltaic cells were determined and checked for each photocell and galvanometer circuit. Specially constructed thermal-radiation calibration devices were employed, each consisting of a calibrated tungsten projection lamp behind a chopper wheel with circular apertures. The lamp's calibration and its distance from the cell gave the sensitivity of the particular circuit. The traces obtained from the chopped light were analyzed to determine the response to short pulses of radiant energy.

The galvanometers employed for most of the traces were Heiland Type 85-6 with a frequency response flat to 60 cycles per second. With the correct damping network, the response was

TABLE 3.1 THERMAL RADIATION, SHOT TEAK

Station	Slant Range	Azimuth	Measured Radiant Exposure	Average Radiant Exposure
	naut mi	deg	cal/cm^2	cal/cm^2
Johnston Island	41.4	0	1.3 1.4 1.4 1.1	1.3
USS DeHaven	85	020	0.31 0.26 0.30 0.29 0.22	0.28
USS Cogswell	164	020	0.065 0.080	0.075
USS Hitchiti	299	060	—	0.0007
C-97 (15,000 ft)	299	060	0.019	0.019*

* Radiant exposure behind window with a transmission of 0.85.

found to be correct for pulses as short as 5 msec to maximum response. Several circuits were set up with Heiland Type 1000D galvanometers with a frequency response flat to 600 cps, which should yield a reliable response to pulses as short as 0.5 msec. Several calorimeters and photocell networks with a wide range of sensitivity were used at each station, thereby increasing the probability of obtaining at least one usable oscillograph trace for each type of instrument at each station.

The calorimeters, skin simulant (Johnston Island only), and photocells at each station were mounted on one or more rigid metal panels, and oriented so as to face the expected point of detonation.

RESULTS

Shot Teak. All the stations were operative at zero time. The instruments were oriented, within a few degrees, toward the expected point of burst. The deviation from the expected point of burst was not great enough to affect the readings. The radiant-exposure measurements and the slant range and azimuth of each station are listed in Table 3.1. Each station had a clear view of the detonation except the one aboard the USS Hitchiti. Intervening clouds prevented a direct view of the event from this station.

None of the black-body receivers on the USS Hitchiti received sufficient energy to give a readable deflection. The radiant exposure for the station was computed from the photocell deflections, the attenuating factors of the circuits, and the relationship between the black-body and photocell data at the other stations.

The black-body receivers at Johnston Island were protected from rain by a thin film of polyvinylidene chloride (Saran), and the radiant exposures have been corrected for the nonselective transmittance of 0.90.

In the C-97 aircraft, the instruments and the rabbits for the retinal-burn studies were behind a plexiglass window. The transmittance of this window was measured to be 0.85 for the solar

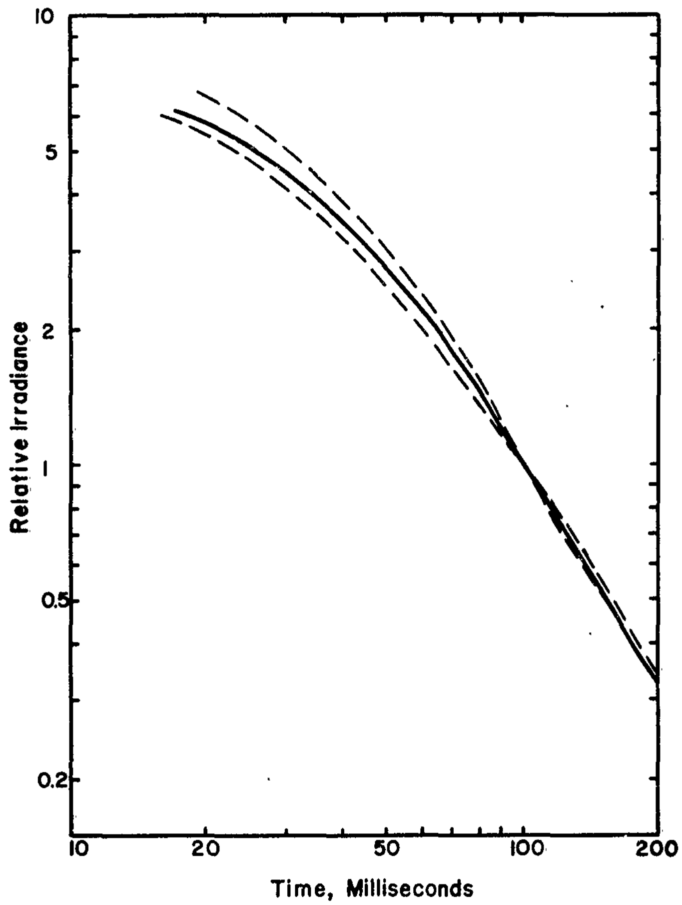

Figure 3.2 Irradiance history, Shot Teak.

spectrum and the silicon photocells employed in measuring the irradiance histories. The radiant exposures listed in Table 3.1 are correct for the retinal-burn studies but must be increased by 15 percent for the radiant exposure incident on the aircraft window.

Most of the photocell traces deflected off scale at the beginning of the shot and then came back on scale in a smooth decay curve which in some cases showed a small dip. Because of the generally large deflections and the limited response of the oscillograph galvanometers, the traces did not yield any data for times less than 10 msec. The dips on several traces were demonstrated to be a result of the large impulse and noncritical damping rather than variations in irradiance decay.

The deflections of the individual photocell traces were normalized about the value at 100 msec and are shown in Figure 3.2. The center line is the average relative irradiance for times from

15 to 200 msec. The two outer curves in the figure show the close range of the irradiance histories about the average, including six traces from the station on Johnston Island, three from the USS DeHaven, three from the USS Cogswell, one from the USS Hitchiti, and three from the C-97. Within the spectral response of the cells, there were no systematic deviations in relative-irradiance history with distance from the burst.

The temperature histories of the skin simulants exposed on Johnston Island are discussed in the next section.

Shot Orange. All the stations were operative at zero time, and any deviation in the orientation of the instruments toward the point of burst was not sufficient to cause an appreciable error in the readings. The radiant-exposure measurements and the slant range and azimuth of each station are listed in Table 3.2. Only the stations on the C-97 aircraft and the USS Epperson had

TABLE 3.2 THERMAL RADIATION, SHOT ORANGE

Station	Slant Range	Azimuth	Measured Radiant Exposure	Average Radiant Exposure
	naut mi	deg	cal/cm^2	cal/cm^2
Johnston Island	20.6	—	1.17	1.08
			1.14	
			1.01	
			0.92	
			1.16	
			1.09	
USS Boxer	75.2	030	0.07	0.08
			0.07	
			0.10	
USS Epperson	88.4	020	0.092	0.09
			0.090	
USS DeHaven	142.8	020	0.008	0.012
			0.016	
C-97 (24,000 ft)	225	060	—	0.012*

* This value was calculated by inverse square law based on the exposure measured on the USS Epperson and corrected for the transmission (0.85) of the aircraft window to give the interior exposure.

a clear line of sight to the shot. The view from the stations on Johnston Island, USS Boxer, and USS DeHaven was to some extent obstructed by intervening clouds. The button calorimeter malfunctioned in the aircraft. The value of radiant exposure for this station given in Table 3.2 was obtained by an inverse square extrapolation of the value measured on the Epperson.

The irradiance history for Shot Orange as measured by the photocell circuits is shown in Figure 3.3, each trace being plotted relative to its value at 100 msec. As for Shot Teak, the irradiance history during the initial irradiance peak was not reliably resolved. The irradiance, in the spectral range of the photocell, remained relatively constant from 40 to 170 msec and then decreased rapidly in another 70 msec. The dashed line, representing the maximum deviation of the nine traces employed, shows a correspondence of each trace of about 2 percent to the average from 20 to 170 msec and a similarity to within 5 percent on the decay portion of the trace. As for Shot Teak, in the spectral range from 450 to 1,000 mμ to which the photocells were sensitive, there was no apparent change in the relative irradiance history among all the stations which ranged from the USS Boxer at 75 naut mi from the burst to the C-97 airborne station at 225 naut mi.

The temperature histories of the skin simulants exposed on Johnston Island are shown in Figure 3.4 for Shots Teak and Orange. The sharp temperature peak for the bare simulant for Shot Teak was indicated by the trace to be at about 5 msec. The deflection was evidently limited by the lack of system response, and a higher temperature coinciding with the irradiance maximum is probable. This characteristic of the bare simulant, observed in the laboratory for exposures less than 0.15 second, is a result of direct absorption of radiation by the thermocouple embedded in the diathermous skin simulant material. This phenomenon, which would be

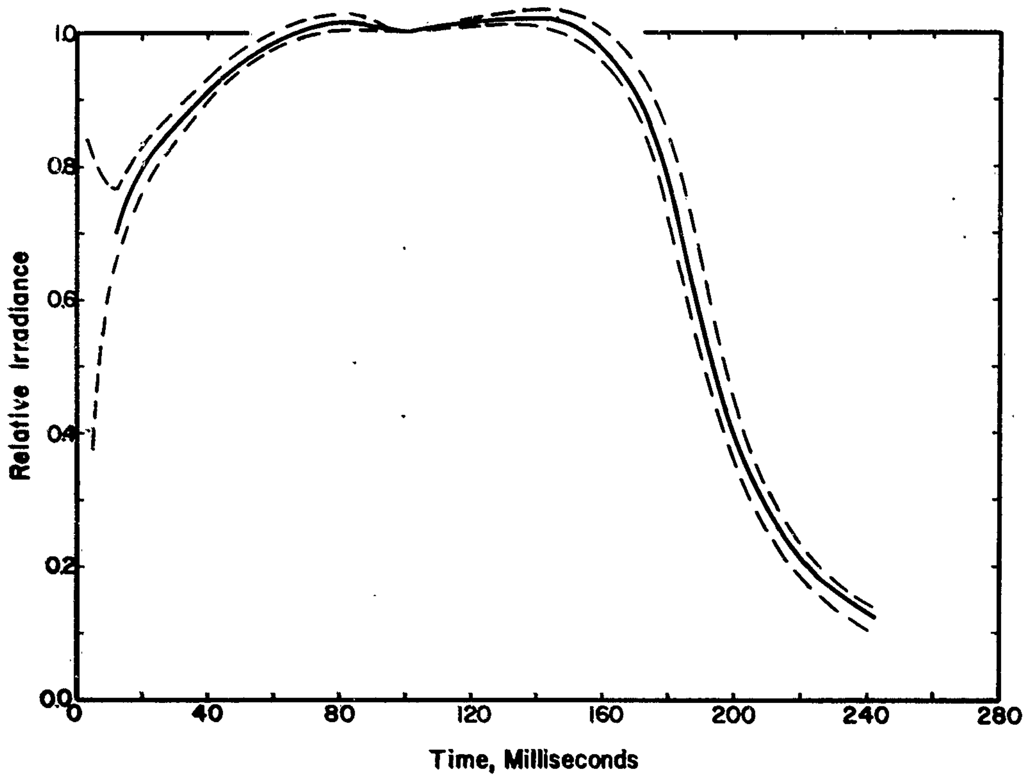

Figure 3.3 Irradiance history, Shot Orange.

anomalous for a homogeneous medium, might be expected to occur as the result of absorption by a discrete pigment layer in human skin. The temperature rises for the bare and for the blackened skin are at least equal to the pain threshold and indicate a probable first-degree burn. If there had been no cloud cover on Johnston Island during Shot Orange, severe burns would have occurred in exposed skin areas.

The temperature rise maxima for the skin simulants on Johnston Island for Shots Teak and Orange due to a radiant exposure of approximately 1.3 cal/cm^2 were about equal to those obtained on Site Olive during Shot Yellowwood where the radiant exposure was 4.0 cal/cm^2. Except for the bare simulant at Shot Teak, the temperature maxima at the thermocouple depth, 0.05 cm, occurred after virtually all the energy had been absorbed. It has been observed for lower-atmosphere bursts that the temperature maxima in the simulants occur before a large portion of the radiant energy is delivered.

DISCUSSION

Table 3.1 shows that for Shot Teak the average deviation of the individual calorimeter readings from the average radiant exposure at the three stations where more than one calorimeter reading was obtained was approximately ±8 percent. The corresponding average deviation of

the calorimeters for Shot Orange as seen in Table 3.2 is ±15 percent. If the readings from the USS DeHaven are eliminated from consideration, then the average deviation in the Orange calorimetry is ±10 percent. The calorimeters are capable of an accuracy of ±5 percent. The somewhat larger scatter observed here is due in part to the reading error in reducing small deflections on the oscillogram, and in part because in most cases it was not possible to perform a postshot instrument calibration on the station in position. In the disassembly of the stations and then reassembly for calibration, corrosion on the cable connectors might have altered the circuit resistance in some of the channels, thereby affecting the calibration.

The probable error of the single calorimeter reading on the C-97 aircraft during Shot Teak is estimated to be ±10 percent. The probable error of the radiant exposure obtained by extrap-

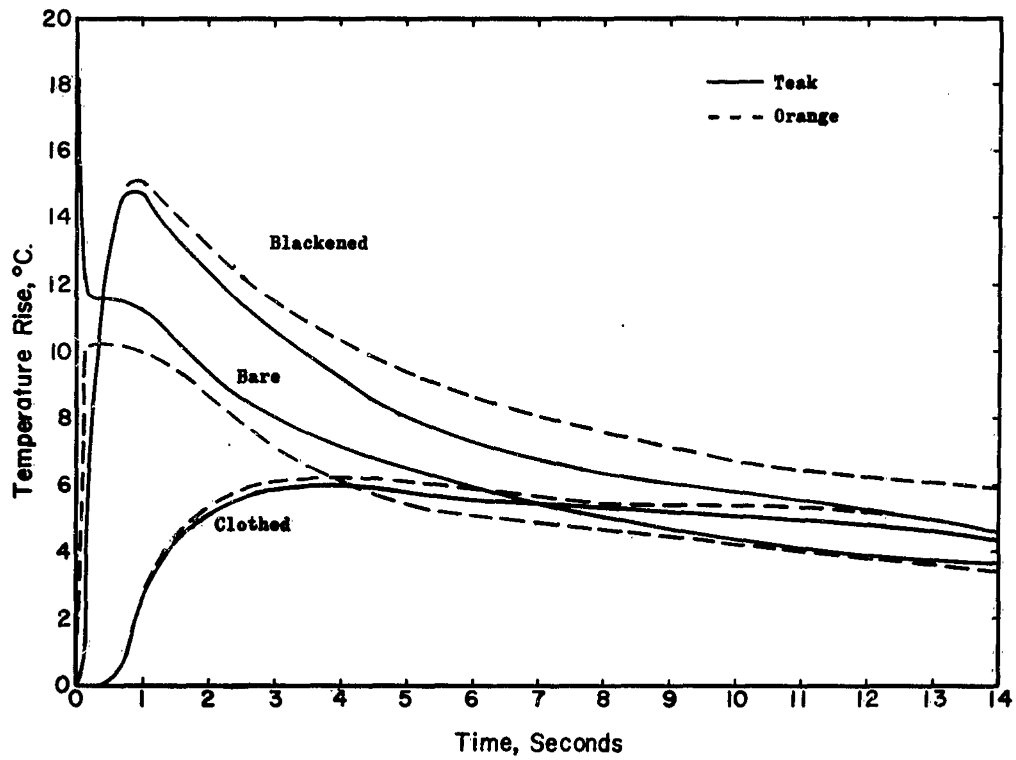

Figure 3.4 Skin-simulant temperature histories for Shots Teak and Orange.

olation for the C-97 during Shot Orange is ±25 percent. The inverse-square relationship between the two line-of-sight stations for Shot Orange would not be expected to hold as closely as for the various stations of Shot Teak, because the extensive cloud background during Shot Orange represented a disturbing influence not present for Shot Teak.

For Shot Teak, the radiant exposures at all the stations, except on the USS Hitchiti, fall close to an inverse-square curve. The deviations of the Q D^2 product for the individual stations were less than 15 percent from the average, indicating only small differences in atmospheric transmissivity. If the average atmospheric transmissivity is assumed to be 0.75, a thermal yield of 1.2 Mt is calculated.

The effect of obscuration of the stations for Shot Orange was so variable that extension of the measurements would be unreliable; however, a lower limit of thermal yield of 0.6 Mt is calculated from the radiant exposure at the USS Epperson.

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of measuring the radiant exposure and irradiance histories at the

earth's surface was attained, except for the resolution of the irradiance histories in the early phase of the pulse and the precise determination of the radiant-exposure values for the obscured station for Shot Teak and the airborne station for Shot Orange. The relative irradiance histories of both shots were obtained during the time that a large portion of the energy which caused retinal burns or other thermal-radiation effects was received. The relative irradiances can be combined with the spatial characteristics of the irradiating sources and the optical properties of the rabbit's eye to furnish an irradiance history and distribution of the retinal image. For the USS Hitchiti station during Shot Teak and for all the stations during Shot Orange, the scattered component of radiant energy may be an appreciable portion of the total, and suitable corrections may be needed for a precise documentation of the retinal stimulus.

For general studies of effects of thermal radiation from high-altitude nuclear bursts, the documentation of the stimulus in future field tests should include better time resolution in total-irradiance measurements and some spectral breakdown of the irradiance history. For studies of thermal effects involving image-forming devices, of which retinal-burn studies are an example, various images of the high-altitude detonation should be formed and documented. Camera-type instruments with special lenses, slits, apertures, and filters could be employed to document the irradiance and size history of images formed by focusing devices.

A large quantity of correlated data for studies of thermal effects, such as retinal burns, can be obtained at one location by adjusting the irradiance with neutral screens, as was done at least partially in the skin-simulant study, and by using lenses or mirrors to adjust image size.

In this way the parameters of particular interest can be varied, without introducing other variables (atmosphere, cloud cover, etc.) which should be controlled in a quantitative experiment.

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